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FORCE FEEDBACK REFUELING SYSTEM FOR UNMANNED AIRCRAFT

Background of the Invention

(1)   Field of the Invention

The present invention pertains to an aerial refueling system for

unmanned aircraft. More specifically, the present invention pertains to an

5   apparatus and method for refueling an unmanned aircraft in-flight. The

apparatus is responsive to sensed forces acting on a refueling receptacle of

the aircraft by a separate refueling probe, to control movements of the aircraft

as it is being refueled to reduce the magnitude of the sensed forces and

thereby maintain the coupling of the aircraft with the refueling probe.

10   (2)   Description of the Related Art

Aerial refueling systems have been used in aircraft for many years.

The systems find extensive use in military aircraft to extend the travel range

and flight time of the aircraft. A typical refueling system employs a receptacle

2232683

on the exterior of the receiving aircraft that is designed to receive and couple with a refueling probe of a fuel supplying aircraft.

In the operation of a typical aircraft refueling system, the refueling probe of the fuel supplying aircraft is extended to a position that is displaced a

5   sufficient distance from the aircraft to enable a receiving aircraft to safely approach and couple with the extended probe. The receiving aircraft has a refueling receptacle on its exterior. The pilot of the receiving aircraft maneuvers the aircraft into a position where the distal end of the supplying aircraft refueling probe will be received in the refueling receptacle of the

10   receiving aircraft.

In known in-flight refueling systems, the distal end of the refueling probe is typically coupled to the receiving aircraft when the probe distal end is received in the receiving aircraft refueling receptacle. The coupling between the refueling probe and the receiving aircraft refueling receptacle enables fuel

15   to be safely transferred from the fuel supplying aircraft to the receiving aircraft. However, the coupling between the supplying aircraft refueling probe and the receiving aircraft refueling receptacle is not sufficiently strong to keep the receiving aircraft coupled to the supplying aircraft. It is necessary that the pilot of the receiving aircraft maneuver the aircraft and hold the aircraft in a

20   position where the coupling between the supplier aircraft refueling probe and the receiving aircraft refueling receptacle is maintained.

With the growing use of unmanned aircraft in military combat and reconnaissance operations as well as in other operations, it has become desirable to perform in-flight refueling of the unmanned aircraft. With the

ability to refuel the unmanned aircraft in-flight, the aircraft can increase its

travel range, increase its flight time, and ultimately improve its performance in

conducting the mission for which the unmanned aircraft has been chosen.

However, unlike refueling operations conducted by manned aircraft where the

5   pilot of the receiving aircraft is capable of maneuvering the aircraft to maintain

the coupling with the refueling probe of the fuel supplying aircraft, in-flight

refueling of unmanned aircraft presents unique problems. It can be

appreciated that the tracking, the capturing or coupling, and maintaining the

coupling of a refueling probe with the refueling receptacle of an unmanned

10   aircraft having little or no visual information on the location of the refueling

probe relative to the unmanned aircraft can be extremely challenging. To

further complicate the desirability of refueling unmanned aircraft, the current

existing fleet of supplier tanker aircraft imposes additional design constraints

on the in-flight refueling of unmanned aircraft. In particular, any in-flight

15   refueling system for unmanned aircraft requiring modifications or upgrades to

the computer control systems of the supplier tanker aircraft may be critiqued

as being too costly and/or impractical to implement.

Summary of the Invention

20   The present invention provides an apparatus and method for refueling

an unmanned aircraft in-flight by maintaining contact between the fuel

receiving unmanned aircraft and a separate refueling probe of a fuel supplying

aircraft. The apparatus and method control movements of the receiving

aircraft, whereby forces acting on a refueling receptacle of the receiving

aircraft by the refueling probe of the supplying aircraft are reduced to a magnitude that is sufficiently small to avoid inadvertent decoupling of the refueling probe from the receiving aircraft refueling receptacle.

The force feedback in-flight refueling apparatus of the invention is basically comprised of a modified refueling receptacle and a computerized control coupler that communicates with the receptacle and the existing control architecture of the receiving unmanned aircraft.

The refueling receptacle of the unmanned aircraft can be any known type of aircraft refueling receptacle that has been modified for the refueling apparatus of the invention. A plurality of load cells are mounted to the refueling receptacle's structural housing. The load cells are strategically positioned on the receptacle housing to measure the magnitude and direction of forces acting on the receptacle housing by the separate refueling probe when in-flight refueling is taking place. In a preferred embodiment, the plurality of load cells are mounted on the refueling receptacle to sense the magnitudes and directions of external forces acting on the refueling receptacle along three mutually perpendicular axes.

The control coupler uses the position and orientation of the refueling receptacle on the aircraft relative to the aircraft center of gravity to transform the component forces acting along the three mutually perpendicular axes at the refueling receptacle into equivalent external forces and moments acting on the unmanned aircraft's center of gravity. The control coupler then sends commands to the aircraft control architecture to cause the aircraft to move in a manner where the transformed external forces and moments acting at the

aircraft center of gravity are reduced or eliminated, and thereby reduces or

eliminates the external forces exerted by the separate refueling probe on the

aircraft refueling receptacle.

5   Brief Description of the Drawings

Further features of the invention are set forth in the following detailed

description of the preferred embodiment of the invention and in the drawing

figures wherein:

Figure 1 is a schematic representation of an unmanned aircraft

10   employing the force feedback in-flight refueling system of the invention;

Figure 2 is a schematic representation of a plan view of the modified

refueling receptacle of the aircraft of Figure 1;

Figure 3 is a schematic representation of a front view of the refueling

receptacle of Figure 2;

15   Figure 4 is a schematic representation of a side view of the refueling

receptacle of Figure 2; and,

Figure 5 is a schematic representation of the aircraft control

architecture and the control coupler of the force feedback in-flight refueling

system of the invention.

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Detailed Description of the Preferred Embodiment

Figure 1 shows a schematic representation of an aircraft (10) with

which the force feedback in-flight refueling system of the invention is

employed. In the preferred embodiment or best mode of the invention, it is

2232683

employed in an unmanned aircraft (10) for refueling of the aircraft in-flight. However, it should be understood that the system of the invention may be employed in other types of aircraft, including manned aircraft. Basically, the force feedback in-flight refueling system of the invention is comprised of a

5   modified refueling receptacle (12) of the aircraft, and a computerized control coupler (14) that communicates with the modified refueling receptacle (12) and the existing control architecture (16) of the aircraft.

Figures 2-4 show schematic representations of the refueling receptacle (12) of the invention. The refueling receptacle (12) is positioned at the back of

10   a slipway (22) that is recessed into the exterior surface (24) of the aircraft's fuselage. The refueling receptacle (12) has a receiver opening (26) positioned in a back wall (28) of the slipway. The receiver opening (26) is dimensioned and configured to receive the distal end of a separate refueling probe (not shown) of a supplier tanker aircraft for refueling of the aircraft (10)

15   in-flight. Although the slipway (22) and refueling receptacle (12) are shown recessed into the exterior surface (24) of the aircraft, the refueling receptacle (12) could be positioned at other locations of the aircraft (10) and the environment shown in Figures 2-4 should not be interpreted as limiting.

A plurality of sensors are positioned in the refueling receptacle (12). In

20   the preferred embodiment of the invention, three pairs of redundant sensors are employed. To simplify the description of the invention, schematic representations of three sensors (32), (34), (36) are shown in Figures 2-4. Although only three sensors (32), (34), (36) are shown in the drawing figures, it should be understood that additional sensors may be employed in the

refueling receptacle (12) of the invention, and that in the preferred

embodiment each of the three sensors (32), (34), (36) is actually a pair of

sensors with each additional sensor of the pair providing redundancy in the

apparatus of the invention.

5   A first sensor (32) of the three sensors is a load cell that is positioned

in the receptacle (12) to sense the magnitude of forces exerted by a separate

refueling probe (not shown) on the refueling receptacle (12) along an X-axis

(42) of the receptacle. A second sensor (34) of the three sensors is a load

cell that is positioned on the refueling receptacle (12) to sense the magnitude

10   of forces exerted by the refueling probe (not shown) on the receptacle (12).

along a Y-axis (44) of the receptacle. The receptacle Y-axis (44) is oriented

perpendicular to the receptacle X-axis (42) and extends to one side of the

receptacle x-axis (42) as shown in Figure 2. A third sensor (36) of the three

sensors is a load cell that is positioned on the refueling receptacle (12) to

15   sense the magnitude of forces exerted by the refueling probe (not shown) on

the refueling receptacle (12) along a Z-axis (46) of the receptacle. The

receptacle Z-axis (46) is mutually perpendicular with both the receptacle X-

axis (42) and the receptacle Y-axis (44). As shown in Figures 2-4, the

directions represented by the arrows of the receptacle X-axis (42), the

20   receptacle Y-axis (44), and the receptacle Z-axis (46) designate the directions

of positive forces acting on the refueling receptacle (12) along the respective

axes, with it being understood that negative forces exerted on the refueling

receptacle (12) are in the opposite directions from those shown in the drawing

figures.

Each of the three load cell sensors (32), (34), (36) are strategically

placed in the refueling receptacle (12) in such a way as to measure the

magnitude and direction of the coupling force acting on the refueling

receptacle (12) by a refueling probe (not shown) coupled with the receptacle.

5 The three-dimensional force vector acting on the refueling receptacle (12) has

components Fx, Fy, Fz in the three-axis system defined at the refueling

receptacle (12). The directions of the positive values of these force

components Fx, Fy, Fz is shown in Figures 2-4. The tensile force Fx is the

force exerted by the refueling probe on the refueling receptacle (12) that tends

10 to pull the receptacle out from its housing in the aircraft fuselage (24). The

other two lateral forces, the side force Fy, and the down force Fz, are normal

to the tensile force Fx and exert stress on the structural housing of the

refueling receptacle (12) in their respective directions. Again, the arrows

shown in Figures 2-4 designate the positive force sign conventions for the

15 force components Fx, Fy, Fz.

The computerized control coupler (14) communicates with the three

sensors (32), (34), (36) of the refueling receptacle (12) and with the control

system architecture (16) of the aircraft (10). The control coupler (14) uses the

mounted position and orientation of the refueling receptacle (12) relative to

20 the aircraft center of gravity (92) to transform the receptacle force components

Fx, Fy, Fz into equivalent external forces and moments acting on the aircraft

center of gravity (92).

Figure 5 is a schematic representation of a modern aircraft control

system architecture. Generally, known aircraft control system architectures

2232683

are comprised of an outer-loop guidance component (52), an inner-loop control component (54), and a control surface mixer (56). The components within the dashed line (58) represent the components of the additional force feedback aerial refueling system of the invention. These include the probe

5   force conversion component, or the previously described computerized control coupler (14). The components also include a series of logical switches (62) which route the appropriate command signals to the inner-loop control component (54) and the aircraft control surface mixer (56).

The outer-loop guidance component (52) controls the steering of the

10   aircraft in response to the input directional commands by computing aircraft load factor (Nz) (64), aircraft role rate (p) (66), aircraft side slip (B) (68), and throttle (72) commands.

The inner-loop control component (54) maintains stable flight of the aircraft by computing commanded moments or angular accelerations (L, M, N)

15   about the respective aircraft x-axis, y-axis, and z-axis in response to the load factor (64), the role rate (66), and the side slip (68) commands, while rejecting disturbances such as wind gusts and maintaining design performance characteristics.

The controls surface mixer (56) sends control surface deflection

20   commands to the aircraft's control surface actuators in response to commanded moments or angular accelerations from the inner-loop control component (54).

The probe force conversions (82) resolve the probe-receptacle coupling forces into aircraft body axis forces and moments and command the

aircraft load factor (64), role rate (66), side slip (68), and throttle (72) to cancel the coupling forces.

The logical switches (62) pass the signals from the probe force conversions (82) to the inner-loop control component (54) when the refueling
5   probe is engaged with the refueling receptacle (12). Otherwise, the logical switches (62) pass the signals of the outer-loop guidance component (52) to the inner-loop control component (54).

Figure 1 represents one hypothetical example of the operation of the force feedback aerial refueling system of the invention. With the refueling
10   receptacle (12) mounted in the aircraft (10) shown in Figure 1, the receptacle (12) is positioned 6-feet in front of the aircraft's center of gravity (92) and 2 feet above the aircraft's center of gravity (92). In addition, the receptacle x-axis (42) is fixed at an angle of inclination of 10° degrees relative to a center line or body x-axis (94) of the aircraft (10).

15   For the example of Figure 1, it is assumed that the refueling probe (not shown) is exerting a positive tensile force on the refueling receptacle (12) of 2000 lbs. To transform the tensile force exerted on the refueling receptacle (12) into the aircraft's body axis system along the aircraft center line (94), the computerized control coupler (14) computes a trigonometric transformation to
20   rotate the refueling receptacle's x-axis (42), downwardly 10° degrees about the receptacle y-axis (44). From basic trigonometry, it follows that:

Fx body = Fx receptacle *cos (-10)

Fx body = 2000 lbs. * 0.9848

Fx body = 1970 lbs.

2232683

Fz body = Fx receptacle *sin (-10)

Fz body = 2000 lbs. *-0.1737

Fz body = -347 lbs.

Because the refueling receptacle is mounted in the aircraft (10) in a

5   position that is off-set from the aircraft's center of gravity (92), the transformed

Fx (96) and Fz (98) forces calculated above also exert a pitching moment or

torque (denoted M) on the aircraft that tends to rotate the aircraft nose

downward. This moment is calculated as follows:

M = Fx body * z off-set – Fz body * x off-set

10   M = 1970 lbs. * -2 ft. - - 347 lbs. * 6 ft.

M = - 1858 lbs. – ft.

Once the coupling forces are transformed to external forces and

moments applied to the aircraft center of gravity (92), the control coupler (14)

can trim the forces out. The external moments exerted on the aircraft center

15   of gravity (92) are cancelled by commanding an equal magnitude but opposite

direction moment. From the example above, the control coupler commands a

positive (nose-up) pitching moment of 1858 lbs. - ft. to cancel the coupling

moment exerted on the aircraft center of gravity (92). External forces are

resolved into commanded accelerations of the aircraft (10) using the aircraft's

20   mass. Again, referencing the example, canceling the coupling force along the

aircraft's x-axis (96), which is coaxial with the aircraft center line (94), requires

a positive acceleration of the aircraft (10) in the direction along the aircraft x-

axis (96), resulting in a speed increase of the aircraft. Accelerations along the

aircraft's x-axis (96) are most effectively obtained with changes in the engine

throttle settings of the aircraft. Canceling the coupling force along the aircraft's z-axis (98) requires a negative z-axis acceleration of the aircraft, resulting in a climb of the aircraft. Accelerations along the aircraft's z-axis (98) are typically obtained with changes in the aircraft's load factor. The

5 magnitudes of these accelerations are inversely proportional to the aircraft's mass.

As explained above, the transformation of the refueling probe coupling force vector components Fx, Fy, Fz acting on the refueling receptacle (12) into the aircraft's body axis system at the aircraft center of gravity (92) results

10 in external forces and moment vectors applied at the aircraft's center of gravity (92). Canceling the external forces and moment vectors is relatively simple, as the moment components directly relate to the desired roll (wings up/down), pitch (nose up/down), and yaw (nose left/right) angular accelerations of the aircraft. It is typical of aircraft trimming capabilities that

15 currently exist in modern aircraft control systems. Thus, the external moment signals (L, M, N) (67) for roll, pitch, and yaw are injected just upstream of the control surface mixer (56) as shown in Figure 5. Canceling the external force vectors requires the use of both aerodynamic control effectors and aircraft throttle. The throttle setting is adjusted according to the force component

20 along the aircraft x-axis (94) and is sent to the propulsion control system. The remaining y and z components of the external force vectors are combined into normal acceleration (Nz) and roll rate (p) commands. Alternatively, if the force component along the aircraft y-axis, which is perpendicular to the aircraft x-axis (96) and z-axis (98), is sufficiently small, then it can be resolved

into a side slip (B) command, allowing the aircraft to "crab" into position. The

normal acceleration (64), roll rate (66), and side slip (68) commands are sent

to the inner-loop control component (54). Finally, a logical discreet that is set

when the receptacle (12) and refueling probe make contact triggers the logical

5 gates to pass the probe force conversion outputs of the control coupler (14) to

the other air vehicle control system components. During the probe/receptacle

contact, the aircraft's outer-loop guidance components (52) are essentially

disabled. Hence, the aircraft effectively becomes a "towed object" behind the

supplier aircraft.

10 Although the subject matter of the invention has been described above

by reference to a specific embodiment, it should be understood that

modifications and variations could be made to the subject matter of the

invention without departing from the intended scope of the following claims.

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